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This paper briefly reviews the methods, concepts, and experimental database used in our laboratory to predict laser, filter, and laser-plus-filter effects on tasks involving visual detection. The modeling approach uses estimates of the spatial distribution of light in the retinal image of the laser source to predict glare, flashblindness, and retinal

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The proposed modeling approach provides a general framework for the interpretation, integration, and application of data from various studies. It has the potential to assess the effects of lasers and eye-protection devices on vision, and to guide visual simulations of the appearance of displays and scenes after laser exposures. The model is far from complete and is complicated by the number of variables affecting laser exposures, vision, and the role of vision in occupational tasks.

Model for Predicting the Effects of Laser Exposures and Eye Protection on Vision

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ABSTRACT

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The proposed modeling approach provides a general framework for the interpretation, integration, and application of data from various studies. It has the potential to assess the effects of lasers and eye-protection devices on vision, and to guide visual simulations of the appearance of displays and scenes after laser exposures. The model is far from complete and is complicated by the number of variables affecting laser exposures, vision, and the role of vision in occupational tasks.

2. INTRODUCTION

Exposure limits for visible-wavelength lasers have been established to prevent retinal damage.[1] Yet, there has long been concern that "eyesafe", high-luminance light exposures might interfere with safe and effective visual task performance.[2-4] To aid in safety, hazard, and protective-measure analyses we have combined and expanded several existing models to predict and compare:

1. Baseline visual function (no laser exposures or eye protection)
2. Effects of laser exposure with eye protection
3. Effects of laser exposures without eye protection
4. Effects of eye protection alone.

The model includes the effects of laser-induced disability glare ("dazzle"), flashblindness, and retinal lesions, but does not include psychological effects or discomfort glare. Application of the model is not limited to laser effects, particularly since much of the model was derived from data and theory for conventional light sources.[2-11] Before providing an overview of the model it is useful to briefly define and describe glare, flashblindness, and visual adaptation.

2.1. Glare and flashblindness

The emphasis of this paper is on "glare" and "flashblindness", which are defined as increases in thresholds for detecting luminance differences *during* and *after* retinal exposure to a high-luminance light source, respectively.[4,7] Both effects can be caused by a single light exposure and are phenomena of visual adaptation: the normal negative-feedback process which scales visual sensitivity to the level of ambient or "background" light.[8]

Fig. 1 shows how an increase in retinal illumination results in "light adaptation": a rapid decrease in visual sensitivity indicated by increased luminance thresholds for detecting a visual target.[8,9] If the high-luminance source continues to illuminate the eye (as shown) light adaptation is followed by a period where thresholds stabilize, indicating that vision is "adapted to" the new luminance level. Both the light-adaptation and the adapted periods of vision comprise the glare effect. Both effects reduce the visual response and visibility of targets imaged on the same parts of the retina as the glare source.

Fig. 1 also shows "dark adaptation" after light levels decrease. Thresholds during dark adaptation decrease until they stabilize at a level determined by the new, lower, adaptation level. Flashblindness is the period of dark adaptation which follows a high-luminance exposure. Short, high-luminance exposures interfere with vision by eliciting successive light- and dark-adaptation responses in the flashed part of the retina. Dark adaptation is typically slower than light adaptation to the same magnitude of luminance change. Light adaptation between two light levels usually takes a few seconds or less, but complete dark adaptation from bright daylight (photopic) levels to the lowest nighttime (scotopic) levels can require about 30 minutes. "Dark" adaptation from a higher to a lower luminance within the photopic range can require less than a second to several minutes depending on the initial and final light levels. This paper mainly concerns adaptation within the photopic range, but the model can also be applied to scotopic vision if appropriate data are provided to estimate several model parameters. Following an overview of the model, adaptation is described in more detail in Section 4 using several empirical, quantitative laws of adaptation.

3. MODEL OVERVIEW

Fig. 2 shows relationships among the main parts of the model described in the following sections.

3.1. Retinal illumination from laser sources

The purpose of the first part of the model is to estimate the distribution of laser light on the retina using empirical data and models which include the effects of intraocular and extraocular scatter. Estimates of retinal distributions of laser light are required by three laser-effects submodels which predict effects at each point of exposed retina. These effects are modeled as functionally-equivalent reductions in target contrast. The model uses the photopic luminous efficiency function for vision as the action spectrum for determining the effectiveness of different laser wavelengths in producing glare and flashblindness.

3.2. Laser-effects submodels

The glare submodel uses the retinal illuminance distribution of laser light to predict reductions in the retinal illuminance and color contrast of visual targets viewed concurrently with a laser glare source.

The glare and flashblindness submodels quantify light and dark adaptation as functionally-equivalent distributions of "Equivalent Background Luminance" (EBL). The EBL varies as a function of time after a laser exposure and is used like a time-varying distribution of physical light to reduce the retinal-image contrasts of targets in the visual field.[2,3,5,8]

Lesion submodels predict retinal lesion diameter and depth using either empirical functions derived from sparse experimental and clinical data, or biophysical models which predict retinal heating as a function of the spatial and temporal patterns of retinal irradiance.[10,11] Lesioned regions of retina are considered permanently

unresponsive to visual targets and are modeled as regions of retina (and optically-corresponding visual field) having zero luminance contrast.

3.3. Vision models

Reduced-contrast scenes from the three laser-effects submodels serve as input to either ORACLE[12,13] or VIDEM.[14] These are empirically-based models of adapted vision which include target-specific maps of luminance-contrast thresholds at each point on the retina. These maps can be used to define a "visual lobe": the region of retina and visual field where a target is above its detection threshold. There is usually only one lobe per target (in the absence of laser effects) and it is normally circular or oval-shaped and centered on the fovea.

The laser-effects submodels specify spatial patterns of EBL which are added to the target- or scene-luminance map on a point-by-point basis (taking into account the point of visual regard). The EBL acts like a veil of light to reduce target or scene contrasts. The resulting reduced-contrast scene is then compared point-by-point with the visual thresholds given by the visual lobes. At some locations on the retina the EBL may reduce the contrast of a target to below the detection threshold, resulting in a "scotoma" (blind spot) in the original visual lobe.

"Absolute" scotomas are regions where vision is lost for all targets, and can result from retinal lesions. Lesion scotomas are largely a function of the laser exposure conditions and essentially independent of target or task conditions. Glare and flashblindness, however, cause temporary, "relative" scotomas which vary in size depending on target conditions. Within the relative scotoma, some targets may be detectable, yet appear reduced in contrast. Relative scotoma size depends on the laser exposure, retinal location, and target conditions. During glare, eye movements change the retinal location of the image of the laser and thus alter the location and size of the glare scotoma. Lesion and flashblindness scotomas remain fixed on the retina since they result from retinal rather than optical effects. Lesion and flashblindness scotomas thus move to obscure different parts of the visual field when the eye moves.

The vision models combine visual lobes with eye-movement effects to translate visual thresholds into measures of target-detection range and search time (for targets having unknown location). The vision models also predict target recognition and identification thresholds based on detection thresholds for various target features.

The vision models are used without the laser-effects submodels to estimate baseline performance for conditions involving no laser exposures or eye-protection devices. Effects of eye-protection devices alone (no lasers) are predicted by altering the visual stimulus which serves as input to the vision models.

3.4. Simulation

The results of the model can be used to guide visual simulations of laser effects for research or training. Artificial scotomas can be created in simulator displays by selectively reducing display contrast in accord with the effects predicted by the model (see Fig. 2). Because flashblindness and retinal-lesion effects are fixed in position on the retina, their simulation is complicated by the need to move their artificial scotomas across the simulator display to compensate for eye and head movements which change the eye's point of regard.

4. THEORETICAL BASIS

4.1. Empirical laws of visual adaptation

The following empirical laws of visual adaptation are used in the model to predict target-detection thresholds for various conditions of laser illumination.

4.1.1. Steady-states of adaptation

When the eye is adapted to a specific background field of luminance (B), the visual response to a target of luminance (T) is a function of the target's luminance-contrast ratio (C), where:

$$C = \frac{T - B}{B} \qquad (1)$$

and where (T - B) is the absolute luminance difference between the target and background regions of the visual field or corresponding retinal images.

When the eye is adapted to (B), the minimum-detectable (threshold) luminance change (T'- B) is proportional to the background luminance:

$$T' - B = k(B) \qquad (2)$$

where (T') is the luminance of the threshold target and (k) is a constant of proportionality. Thus:

$$k = \frac{T' - B}{B} \qquad (3)$$

where (k) defines the threshold contrast ratio. The value of (k) is constant over a wide range of background luminance conditions, but varies as a function of a large number of target conditions such as retinal image size, location, and duration.[8] If (k) is known, Equation 3 can be used to predict the target luminance required to permit visual detection when the eye is fully adapted to a specific background luminance.

Unfortunately, there are no general theories of spatial vision which can successfully predict (k) for a range of arbitrary target conditions.[15,16] Current practical applications thus involve experimentally measuring (k) for each target of applied interest (if the target is specifically known), or using parametric, empirical models which base estimates of (k) on detection data for circular targets of various diameter, area and duration.[12-14]

4.1.2. Dynamic states of adaptation

4.1.2.1. The equivalent background luminance

Thresholds at any instant during adaptation are like those for fully-adapted vision to a background of a higher luminance.[5,8] This is the basis for using the "Equivalent Background Luminance" (EBL) to quantify adaptation effects. The EBL is the additional amount of light which would be needed to raise a target's fully-adapted threshold to equal the threshold at some instant during adaptation. The EBL acts like a veil of light added to the retinal image

of the scene to reduce its luminance (and color) contrast. The EBL varies as a function of retinal illuminance (E) and time (t) for both dark and light adaptation. Thus:

$$EBL = f\ (E,t) \tag{4}$$

where the value of (E) may also vary as a function of retinal position (as discussed in section 4.2.). For special viewing conditions, the EBL is related to the luminance which matches the brightness of afterimages seen after high-luminance exposure.[17-19]

The great utility of the EBL is that it is practically independent of visual target and task conditions.[8] Thus the adaptation effects of various laser exposures can be estimated for a range of target conditions using estimates of the EBL obtained in studies using only one kind of target (e.g., one of a given size or shape). This method greatly reduces the number of experimental measurements needed to support a practical model of adaptation and facilitates comparisons of results among studies using different target and task conditions. The EBL approach also theoretically separates laser and target effects in terms of EBL and (k) values, respectively.

4.1.2.2. Dark adaptation

Consider dark adaptation at a particular retinal location and time after laser exposure. The effective contrast at a particular retinal location and instant will be reduced from C to C' as a result of the addition of the EBL to both target and background fields:

$$C' = \frac{(T + EBL) - (B + EBL)}{B + EBL} = \frac{T - B}{B + EBL} \tag{5}$$

This functional reduction in luminance contrast renders targets undetectable if $C' < k$ (where the value of (k) is determined by the target conditions and steady-state adaptation to B + EBL). The EBL will also reduce perceived contrast for targets of higher, suprathreshold contrast (i.e., where $C' > k$).

We have derived curves of EBL as a function of flashblindness recovery time for various conditions of flash luminance using parametric data collected by Miller.[5,20] These studies give luminance thresholds (T') for targets presented on a "black" background as a function of time after exposure to uniform-luminance, spatially-extended, non-laser flashes. The EBL at each point in time during flashblindness recovery was estimated from Equation 5 by calculating the additional luminance required to reduce the target to its adapted photopic contrast threshold ratio (k). For example, if a target with k = 0.05 required a retinal illuminance of E = 100 trolands (tds) for detection 10 sec after a flash, then the sum of the EBL and background luminance was estimated to be 2000 tds at t = 10 sec. A set of EBL "decay" functions are shown in Fig 3.

The EBL given in Fig. 3 is in cd/m^2. This is the EBL in the visual field rather than on the retina, and was obtained by dividing the equivalent retinal illuminance (tds) by the pupil area. Note that the upper curve in Fig. 3 describes data for all exposures $\geq$7.6 log td-sec. This means that flashblindness recovery times do not continue to increase for exposures >7.6 log td-sec (unless retinal damage occurs).[4,20] This "saturation" effect occurs at a photometric exposure which insures that each molecule of visual cone-receptor photopigment absorbs at least one photon of light.[8]

4.1.2.3. Light adaptation

The EBL also varies during light-adaptation. For any instant when a glare source increases the retinal illuminance by an amount (E):

$$C'' = \frac{(T + E + EBL) - (B + E + EBL)}{B + E + EBL} = \frac{T - B}{B + E + EBL} \qquad (6)$$

where (C") is the reduced effective contrast for a target of constant luminance (T). This effect is a joint result of the physiological light-adaptation response (given by the EBL) and the optical effect of the additional light (E) from the glare source. Data to predict the EBL as a function of time after the onset of a glare source are limited to relatively weak glare illuminances of <4 log tds.[9]

4.2. Retinal images of laser sources

To predict glare and flashblindness it is crucial to know how (E) varies across the retinal image of the laser source. Retinal images of laser and non-laser optical point-sources have a high central peak but are spatially extended.[6,21,22] This effect is not due to the common Gaussian distribution of energy in the laser beam, but to optical scattering in the ocular media alone or in combination with extraocular scattering by the atmosphere and optical materials as shown in Fig. 4.

4.2.1. Intraocular scattering

The scattering properties of the eye are relatively well-known.[6,21,22] We have modified the empirical, analytical function given by Vos[6] to estimate the spatial distribution of light on the retina for point-source exposures. The Vos function describes intraocular scattering in young eyes from a mathematical fit of data pooled from a number of studies. Equation 7 is the version of the Vos equation which we use for modeling retinal distributions for glare and flashblindness.

$$E = (a)(x)(10)[(\theta + 0.02)^{-2} + (\theta + 0.02)^{-3} + 10^{5} e^{-(\theta/0.02)}] \qquad (7)$$

Equation 7 gives retinal illuminance (E) as a function of the angular distance (θ) from the center of the retinal image for exposures to visible wavelengths which vary in corneal illuminance (x). The expression includes (θ) from 0 to 100 deg. For glare, (E) is given in tds as a function of (a): the smaller of pupil area or laser-beam area at the cornea in mm^2; and (x): the illuminance from the point-source measured at the cornea in $lumens/m^2$. For flashblindness modeling, (E) is given in td-seconds as a function of (x) in Lux-sec and (a) in mm^2. Equation 7 indicates that the shape of the log (E) vs (θ) distribution for the eye is invariant with changes in corneal illuminance and pupil size.

Equation 7 can also be used to estimate retinal irradiance distributions for visible wavelengths when (x) is specified in terms of a corneal irradiance. These retinal-irradiance distributions are used in various biophysical models which predict retinal lesion diameter and depth based on retinal heating.[10,11]

4.2.2. Extraocular scattering

Retinal-image distributions for light propagated through optical materials can be inferred from behavioral and optical studies.[23-25,28] The conditions sampled by these experiments is limited, but the data show that optical

materials such as the atmosphere and windscreens can substantially broaden the retinal-image of a point-source, and often contribute more scattering than the amount contributed by the eye alone. Extraocular scattering can vary significantly with wavelength[26], yet intraocular scatter does not.[27] Unfortunately, there is no general theory or parametric data which can be used to predict the retinal-image-broadening effects of various optical materials and atmospheric conditions.

4.3. Point-by-point independence

A critical requirement of the foregoing modeling approach is that visual adaptation proceeds independently across the retina. This approach is supported by empirical evidence that adaptation is practically independent for neighboring parts of the retina.[5,6,8]

5. MODEL RESULTS AND IMPLICATIONS

An example of the application of the point-by-point method is shown in Fig. 5 for the simple case of intraocular scatter alone. The upper curve of Fig. 5 shows the retinal-illuminance distribution predicted using Equation 7 for an eye exposed to a single 530-nm, 20-nanosec flash with a corneal irradiance of 1.2 mJ/cm^2. The pupil diameter at the time of the exposure was assumed to be 3.5 mm. The two curves at the bottom of Fig. 5 are predictions from the flashblindness submodel using the decay functions of Fig. 3. These two curves show distributions of EBL at different times after the exposure. Spatio-temporal decay functions of this sort play a central role in modeling flashblindness and light-adaptation. These functions are used to predict when the effective contrast is at or above threshold across the retina. Flashblindness recovery at any exposed part of the retina is thus predicted to occur at the instant when $C' = k$.

As shown in Fig. 6, the type and size of laser effects on the retina is a joint function of retinal thresholds and the retinal-image distribution of the laser exposure. If provided with the appropriate data, the model can predict the size of each effect. The effects shown in Fig. 6 are predicted from a reasonable ordering of retinal thresholds from lowest to highest for glare, flashblindness, thermal (photocoagulation), and hemorrhagic lesions, respectively.[28] The result is four concentric zones on the retina, one for each of the four effects. The diameter of each zone depends on the threshold for each effect. In this example the glare effect is largest and the source of the hemorrhagic lesion is smallest (Note: The hemorrhage is hypothesized to be secondary to initial retinal trauma; the blood could be located in the subretinal, retinal, or vitreal tissues; and the pattern and size of the blood shown are arbitrary). The four effects reduce vision in the optically-corresponding parts of the visual field imaged on the affected retinal zones. Lesion effects (if immediate) will preclude glare and flashblindness within lesioned zones, but glare and flashblindness can share part of a zone since glare occurs during, and flashblindness occurs after the laser exposure.

Eye-protective devices and optics could affect the size of retinal-effects zones by altering the amplitude and shape of the retinal image of the laser. Especially important is the case where eye protection reduces the amplitude of the retinal distribution to an "eye-safe" level (i.e., where the peak of the distribution is less than the thermal lesion threshold). For these conditions, the model shows that glare and flashblindness zones may still remain, but will be reduced in size by the eye-protective device. The net effect of an eye protection device on glare and flashblindness is predicted by the net effects of the device on the retinal image of the laser and the luminance and color contrasts for the target and background fields.

Finally, consider how each laser effect might increase in size for progressively increasing corneal and retinal illuminances from a laser. If the intensity of the retinal illuminance scales linearly with corneal exposure, then thresholds for each effect will be reached at greater distances from the center of the laser image. If thresholds are independent of the retinal-image distribution, then each effect would grow in size at the same rate. This is shown in Fig. 7 for all but the hemorrhagic lesion effect, which was drawn as an exception based on the expansive properties of hemorrhages and the desire to illustrate effects of a faster growth rate for one of the zones. A faster growth rate for an effect with a threshold higher than another would result in an eventual intersection of curves as shown in Fig. 7. A more complete empirical model of lesion effects requires knowledge of the size and type of lesion resulting

from a range of laser exposure conditions. Thresholds for lesions of minimal size (30-50 microns subtending 6-10' arc) are known for a number of conditions, but little is known on how lesion size varies with exposure energy.

These results provide the input to the vison models. Further discussion of the impact of laser effects on the results of the vision models is beyond the scope of this paper.

6. CONCLUSIONS

The model provides a systematic, integrative approach to predict laser effects on vision. The general results demonstrate the value of a combined retinal-effects model and emphasize how multiple laser effects may combine to reduce vision by a greater amount than predicted by a single-effects model.

Application of the model is currently limited. Additional data are needed to estimate various parameters and to test the validity of a number of basic working hypotheses. We conclude with the following list of *some* of the major unresolved issues:

1. The need for a practical general model of spatial vision to predict (k) or contrast thresholds for arbitrary targets.

2. The effects of various optical materials and atmospheric conditions on the extraocular-scattering and retinal-image distributions.

3. The need for more information on the specific visual cues available and used in occupational tasks.

4. Adaptation effects of multiple exposures and the effect of pulse repetition rates.

5. Upper and lower limits on reciprocity (additivity) for calculating the accumulated exposure for predicting flashblindness after single and multiple flashes.

6. Eye movement determinants of the retinal location of exposures for single and multiple flashes.

7. Visual fixation behavior with central scotomas and the ability to use spared regions of retina.

8. The need for a retinal lesion model for short-pulse exposure conditions which cause damage by photo-acoustic and other non-thermal processes.

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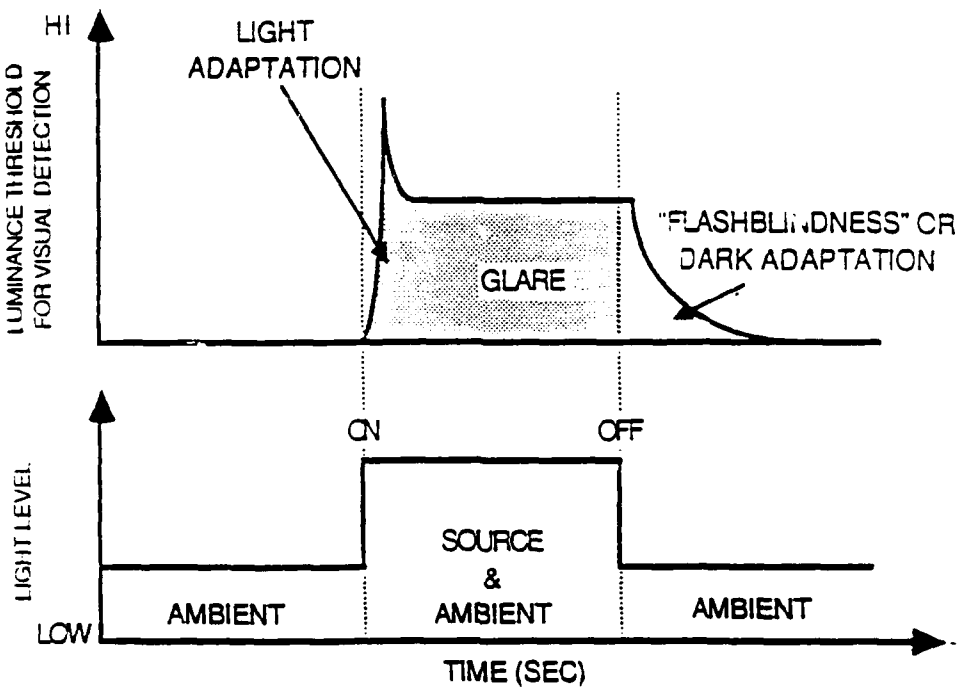

Fig. 1. Glare and flashblindness in relation to changes in retinal illumination and light- and dark-adaptation responses.

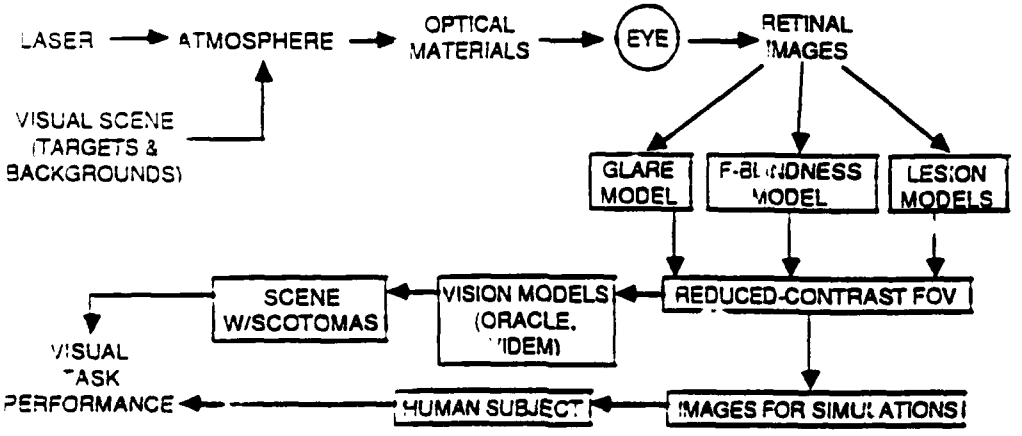

Fig. 2. Flow-chart of major components of the model.

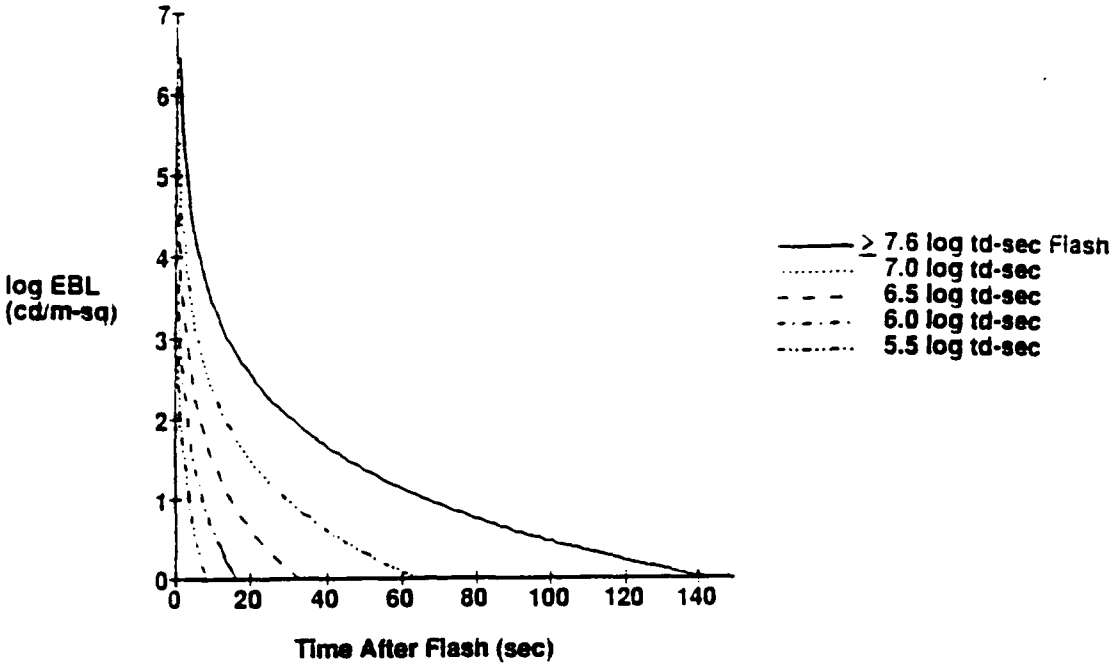

Fig. 3. log EBL as a function of time after flashes of various levels of retinal illuminance.

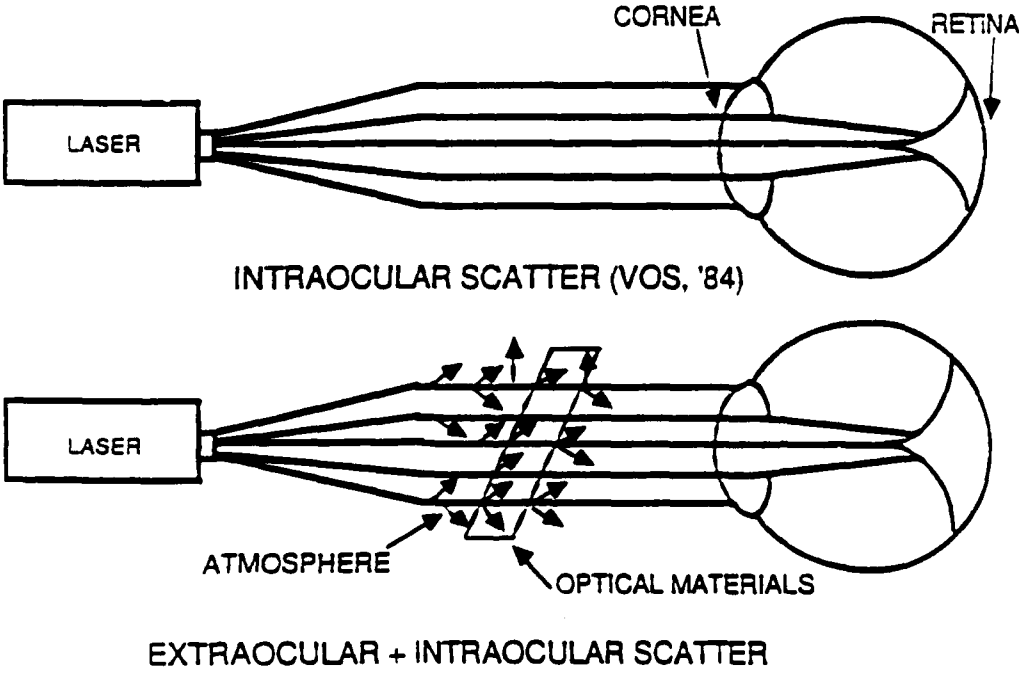

Fig. 4. Optical-scattering effects on the distribution of light in the retinal image of a laser point source (intrabeam viewing): effects of intraocular scatter (top); effects of extra- and intra-ocular scattering (bottom).

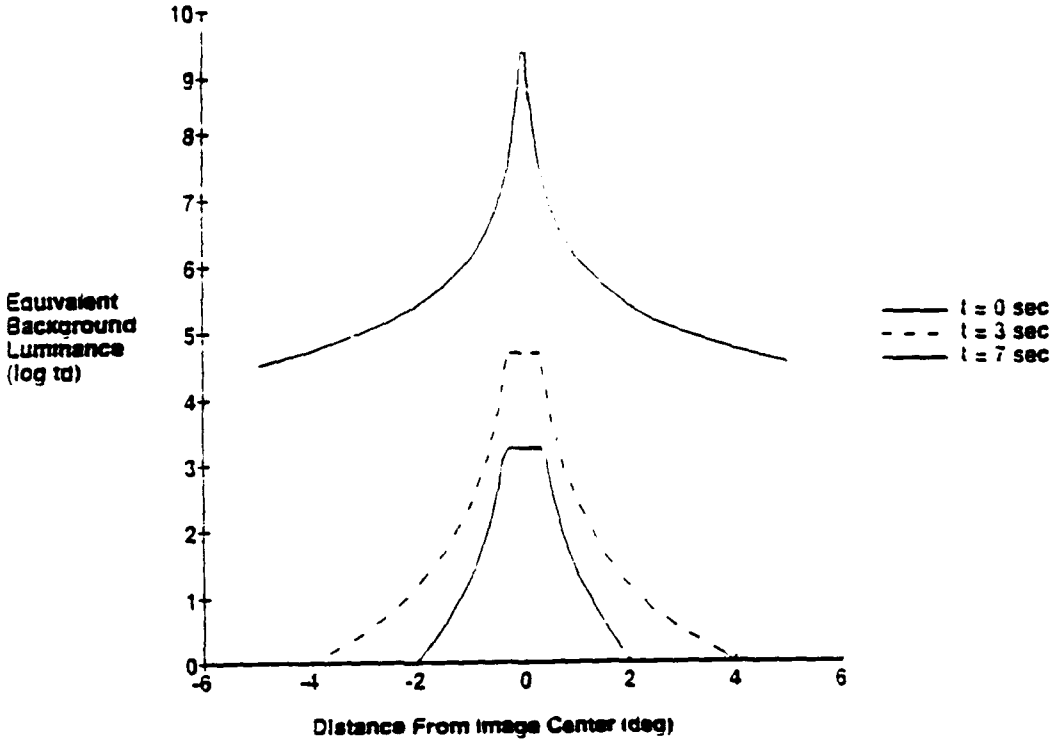

Fig. 5. Spatial profile of EBL as a function of time after exposure with retinal-illuminance profile shown in upper curve.

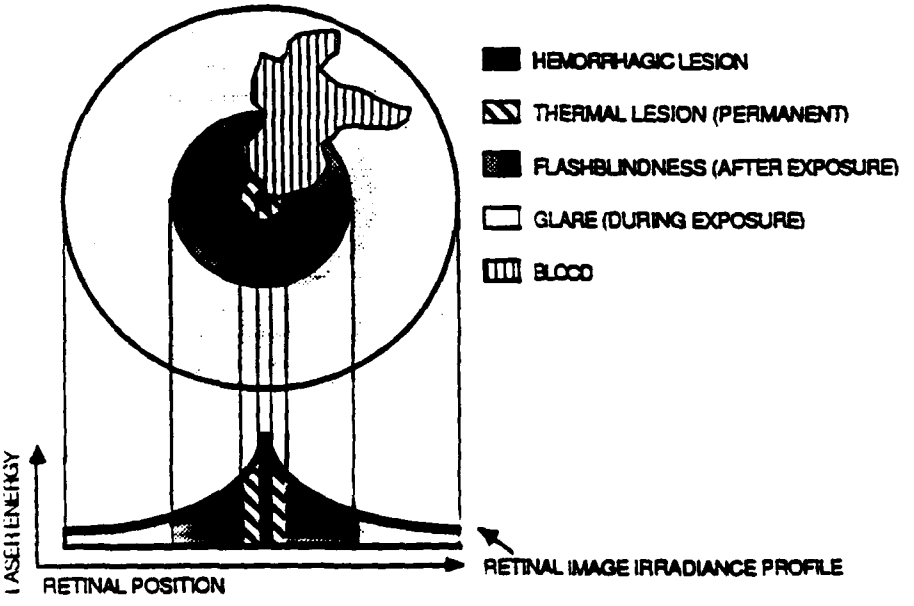

Fig. 6. Type and size of retinal effects is a joint function of their retinal thresholds and the retinal-image distribution of the laser.

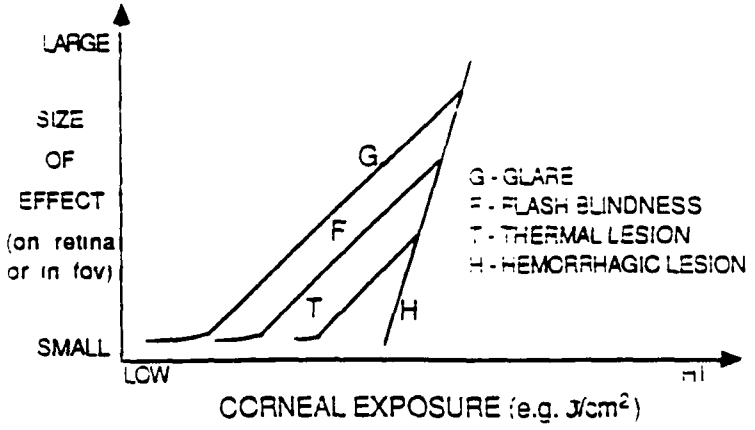

Fig. 7. Predicted size of retinal region affected by various laser effects as a function of corneal exposure. See text for assumptions and methods.